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THE RESISTANCE OF HY130 STEEL TO ENVIRONMENTAL CRACKING IN SEA --ETC(U)
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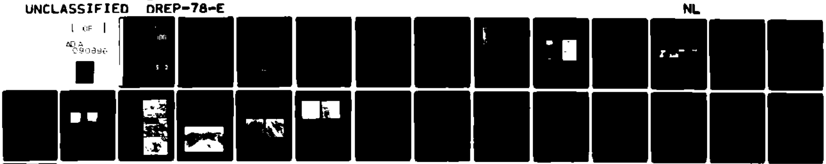

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Materials Report 78-E

THE RESISTANCE OF HY130 STEEL TO ENVIRONMENTAL CRACKING IN SEA WATER

T.P. Nikiforuk and J.A.H. Carson

December 1978

Research and Development Branch
Department of National Defence
Canada

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Approved

Section Head

Chief

RESEARCH AND DEVELOPMENT BRANCH

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ABSTRACT

The Electroslag Refined (ESR) and the Air-Melt Vacuum Degassed (AMVD) forms of the HY130 low alloy steel, along with three weldments, AX140 MIG and E12018 and E14018 stick, have been evaluated for their resistance to environmental cracking under static loading in natural sea water.

It was found that under both free corrosion and under cathodically protected conditions, cracks will not initiate in either the ESR or AMVD alloys, their heat-affected zones, or the three weldments, at static stresses close to the yield.

For freely corroding HY130 alloys and weldments the lowest threshold stress intensity factor (K_{Iscc}) for crack propagation was 95 MPa$\sqrt{m}$ for the E12018 stick weldment. The lowest threshold ($K_{I_{HAC}}$) for crack propagation under cathodic protection at zinc potential was 50a$\sqrt{m}$ (also for the E12018 stick weldment). Both of these thresholds are relatively high for high strength steels.

The tests indicated that a stress relief anneal of two hours at 620°C, followed by either furnace or air cooling, does not markedly affect the environmental cracking resistance under static loading of the two types of HY130 parent material, or of the three weldments.

For the HY130 alloys and the three weldments studied, fractographic evidence supports a hydrogen-induced cleavage mechanism for both stress corrosion cracking and cracking under cathodic protection.

INTRODUCTION

The growing interest in high performance ships, such as hydrofoils, has necessitated a corresponding interest in high strength materials. These materials, which have a high strength to weight ratio, must meet specific requirements, such as ease of fabrication, high toughness at low temperatures, and good resistance to environmental cracking. While there are several types of alloys which can meet the requirements for strength, low temperature toughness, and ease of fabrication, the selection becomes much more limited when the resistance to environmental cracking is considered.

The first high performance ship in the Canadian Navy was the hydrofoil HMCS BRAS d'OR. The cracking that occurred in the 1700 MPa (250 ksi) Maraging Steel foils of this ship severely limited the evaluation of the hydrofoil concept. The cracking resulted from unexpectedly high residual welding stresses and a low resistance of the welded material to crack initiation under both the freely corroding and the cathodically protected conditions.[1,2]

As part of the DND program to determine the suitability of a number of high strength alloys for use in future high performance vehicles and equipment, DREP undertook an evaluation of the high strength low alloy steel called HY130, which the United States Navy has recognized as an acceptable material for hydrofoil construction.[3] The HY130 is a weldable high strength steel that can be fabricated readily without a post welding heat treatment. The steel has a yield strength (σys) of 896 MPa (130 ksi) and is characterized by having very high ductility and a low work hardening rate for such a high yield strength, and it has been reported to have excellent toughness and environmental cracking resistance.[2,3,4,5]

The HY130 steel used in this investigation was obtained in two forms, Electroslag Refined (ESR) and Air Melt Vacuum Degassed (AMVD). Compositions are given in Table I. The ESR material with its higher purity is recognized as having superior properties to the AMVD metal, but is not as readily available. This study was conducted to determine the resistance to crack initiation and crack propagation of these two steels in natural sea water, both under freely corroding and cathodically protected conditions.

Since it is envisaged that high strength alloys would be used predominantly in the welded form, resistance to cracking of the welded material is of paramount concern. Welding introduces the problem of residual stresses,

and therefore part of the evaluation involved a look at the effect of stress-relief heat treatments.

TABLE I

APPROXIMATE COMPOSITION OF HY130 STEELS AND WELD RODS (WT%)

	Fe	Ni	Cr	Mn	Mo	C	V	Si	S
ESR	bal	5.4	0.59	0.73	0.49	0.1	0.06	0.2	0.003
AMVD	bal	5.3	0.59	0.78	0.49	0.1	0.06	0.3	0.012
E12018 weld	bal	2.3	0.74	1.6	0.37	0.1			.014
E14018 weld	bal	3.5	0.55	0.9	0.64	0.1			.005
AX140 wire	bal	2.1	0.88	1.9	0.54	0.1	<.01	0.3	.008

Welding Procedures

All welding was on 1-inch thick plate, double-vee groove. The welding procedures were as follows:

a) For the E12018 and E14018 stick weldments, 3.0 mm (0.125 in) stick electrodes were used for the root pass and 4.0 mm (0.16 in) electrodes (weaved) for the remainder of the multiple passes. The electrodes were stored at 180°C (350°F) for 48 hours prior to reversed polarity welding at a current of 170A.

b) The AX140 MIG welding was performed using an Argon - 2% oxygen shielding gas and 0.9 mm (0.035 in) filler wire (MIL 140S) stored at 30°C (85°F). The parent plate was preheated at 120°C (250°F) and welded with multiple passes (all weave) at 28V and 225A.

Simulated Heat-Affected-Zone

Because of the difficulty of restricting crack growth in a pre-cracked cantilever beam specimen to the heat-affected-zone (HAZ) of actual welds, the HAZ structure was simulated by heat treating as-received material at 1070°C for one-half hour, followed by water quenching. The resulting martensitic structure was similar to the HAZ of an actual weld as can be seen by comparing Figures 1a and 1b.

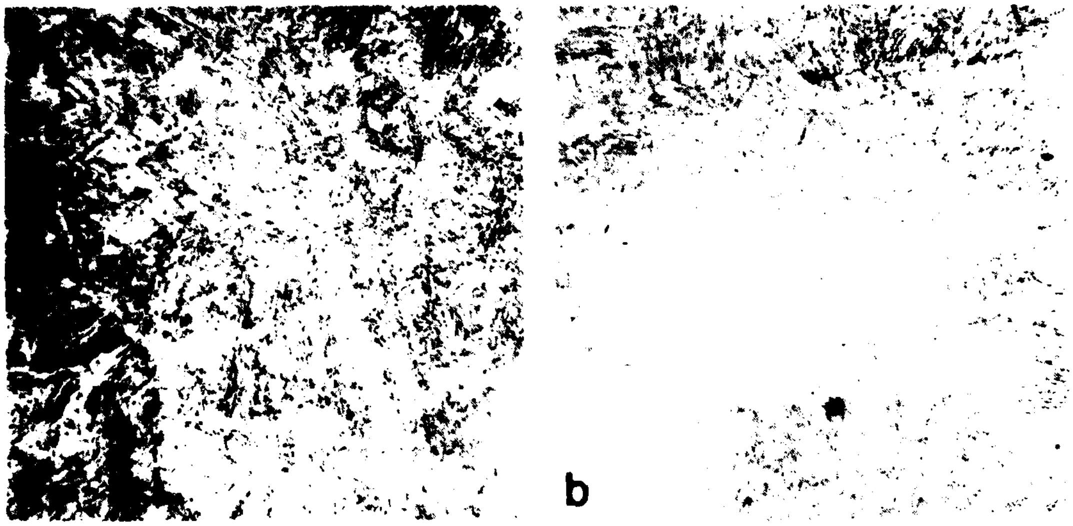


Figure 1

a. Simulated heat affected zone (HAZ) microstructure (Magnification 170x)

b. Actual heat affected zone microstructure (Magnification 170x)

Stress-Relief Heat Treatments

For the stress-relief heat treatment, the test specimens were held for two hours in a box furnace at 620°C (air atmosphere), followed by either furnace or air cooling.

The tensile properties of the parent, welded, and heat-treated metals are given in Table II.

TABLE II

TENSILE PROPERTIES OF TEST MATERIALS

MATERIAL	YIELD STRENGTH				ULTIMATE STRENGTH			
	As Received		Stress-Relief Annld Furn Cld		As Received		Stress-Relief Annld Furn Cld	
	MPa	Ksi	MPa	Ksi	MPa	Ksi	MPa	Ksi
ESR HY130 Parent	950	(138)	869	(126)	1028	(149)	959	(139)
AMVD HY130 Parent	904	(131)	800	(116)	988	(143)	925	(134)
E12018 Stick Weld	869	(126)	800	(116)	945	(137)	904	(131)
E14018 Stick Weld	850	(123)	731	(106)	938	(136)	932	(135)
AX140 MIG Weld	840	(122)	766	(111)	966	(140)	925	(134)

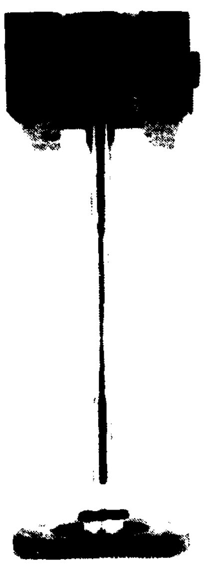
Note: Elongation not measured, but all specimens broke in ductile manner.

TEST PROCEDURES

Crack Initiation

Crack initiation studies were made on smooth tensile specimens as shown in Figure 2a. The specimens were machined with the long axis transverse to the plate primary rolling direction and, in the case of welded specimens, transverse to the weld. Gauge sections were ground to an 8μ inch finish. After degreasing with hexane, the specimen was immersed in continuously flowing natural sea water at 8° - 12°C with a uniaxial (within ±2%) tensile load applied by means of a lever system as shown in Figure 2b.

a



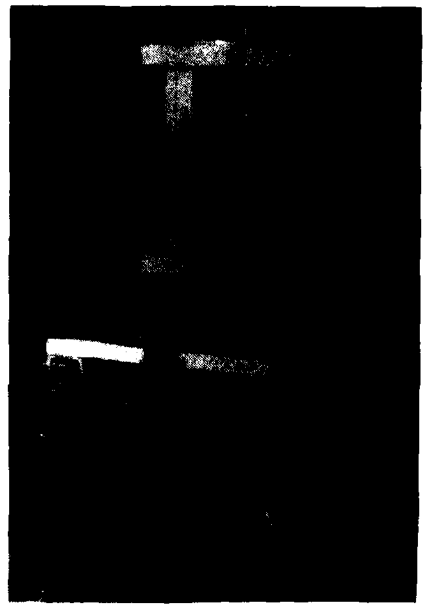


Figure 2.

a. DREP tensile specimen used for environmental crack initiation tests.

b. DREP environmental tensile testing machine.

Cathodic protection at approximately -1.03 volts vs Ag/AgCℓ was provided by galvanically coupling the specimen to zinc. An impressed current system with a zinc anode was used to maintain specimen potentials at -1.2 volts (vs Ag/AgCℓ).

A specimen was considered immune from crack initiation under the test condition if it did not fail within a year.

Crack Propagation

The evaluation of the crack propagation properties of the HY130 materials was made on the precracked cantilever beam type of test specimen proposed by B.F. Brown.[4] The specimen dimensions are given in Figure 3. The equation (after Brown[4] and Kies[5] et al.) used to calculate stress intensity factors for this type of specimen was:

$$K = \frac{4.12\, M_o \,(d^{-3} - d^{3})^{1/2}}{BD^{3/2}} \quad \text{units MPa(m)}^{1/2}$$

where M_o = moment acting at fatigue crack (Newton-metres)
B = width of specimen (metres)
D = depth of specimen (metres)
$d = 1 - \frac{a}{D}$
a = depth of defect* = notch (n) + fatigue crack (metres)

Note: MPa = 6.89 ksi
$\text{MPa(m)}^{1/2} = 1.1\ \text{ksi(in)}^{1/2}$

*Average depth of fatigue crack front. (Crack fronts were relatively flat as can be seen in Figure 5.)

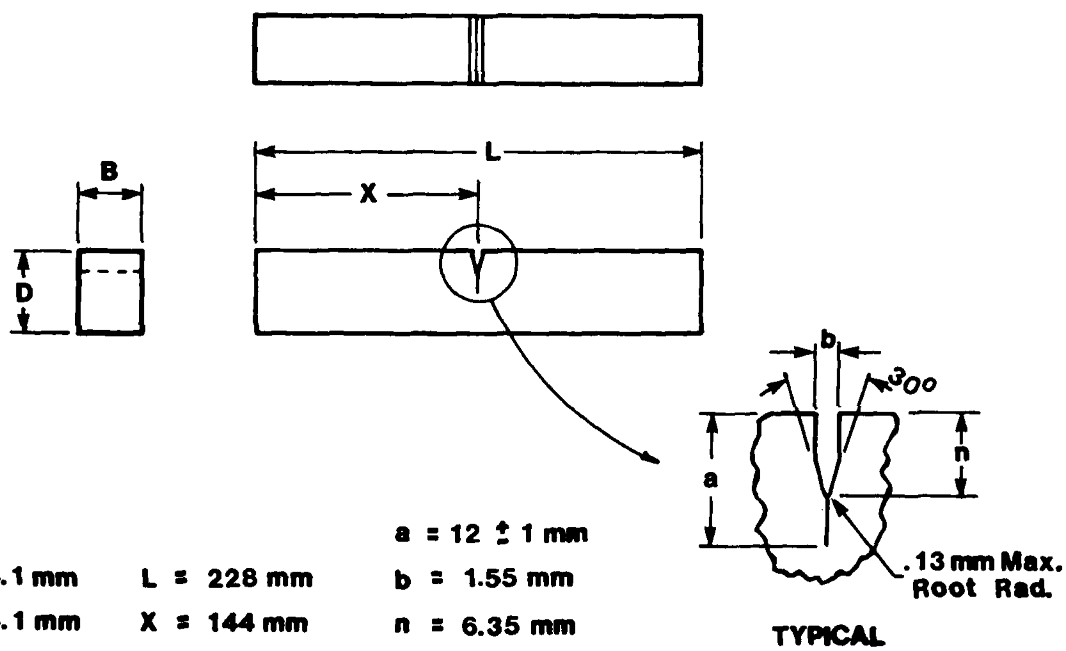


Figure 3. Precracked cantilever beam specimen used for environmental crack propagation tests.

Test specimens were cut from parent and welded plate with the long axis transverse to the primary rolling direction, and the notch ground parallel to the primary rolling direction (T-S orientation). For the welded specimens the longitudinal axis was transverse to the weld bead and the notch was ground into the weld metal. After specimens were ground and polished they were heat treated, if required, and then precracked by fatigue to give a total defect-to-depth ratio (a/D) of approximately 0.5.

Tests were performed on DREP cantilever test racks as shown in Figure 4a. For the in-air tests, weights were added slowly until the specimen failed.

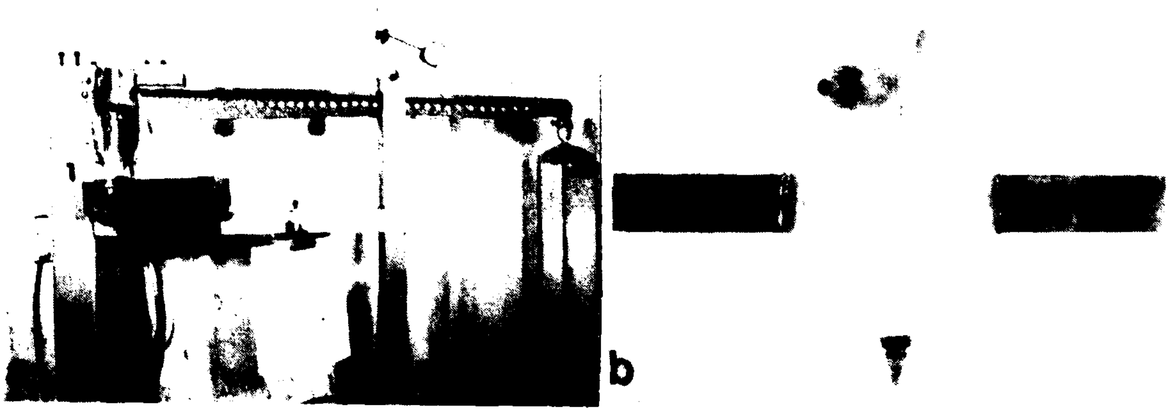


Figure 4.

a. DREP cantilever test rack for crack propagation studies

b. Stress corrosion and hydrogen cracking test cell (1/3 actual size)

For the environmental cracking tests, specimens were mounted in polyethylene bottles sealed with a silicone sealant as shown in Figure 4b. Once-through natural sea water at 8°-12°C was fed in at the bottom of the bottle and drawn off at the upper spigot. If the specimen was to be cathodically protected, it was metallically coupled to the zinc anode prior to filling the bottle with sea water and adding the pre-determined load. The load was applied to the specimen by releasing a support cam on the intermediate stanchion.

The load was chosen to achieve a pre-determined stress intensity factor on the assumption of a flat fatigue crack of the depth showing at the

sides of the specimen. After fracture, the "true" depth "a" was taken as the average across the pre-crack face. As will be noted in Figure 5, the fatigue cracks were quite flat.

If a specimen did not show crack propagation within two months, it was considered that it was not going to fail.

Where a fracture face was to be subjected to an electron microscope fractographic examination, the corrosion products (or cathodic deposits) were removed from the fracture surface by cathodic cleaning in a dilute solution of H_2SO_4 inhibited with 0.1% Rhodamine B.

RESULTS AND DISCUSSION

Crack Initiation

It was found that under static loading in sea water, with stresses just below the yield, i.e. around 820 MPa or higher) cracks did not initiate in either of the two types of HY130 steels, whether As-Received, Welded, and/or Stress Relieved, and whether freely corroding or cathodically protected at -1.05 or -1.2 volts (vs Ag/AgCℓ). By contrast, cracks initiated in welded Maraging Steel (UTS = 1720 MPa), whether freely corroding or cathodically protected at -1.05v, at stresses as low as 550 MPa.[1]

Crack Propagation

The results of the pre-cracked cantilever beam fracture toughness evaluations are given in Table III. Where two or more specimens were evaluated under a given set of conditions, then the range of the results is given. Most of the results in Table III are not truly valid fracture toughness indices because the dimensions of the specimens were too small to meet ASTM criteria. While the undersized thickness of the specimens should result in high values, there is evidence[8,9] that the short ligament length [(D-a) in Figure 3] results in lower values, and this latter effect is dominant, at least for the dry fracture results.

The relatively ductile failures observed in these cantilever beam dry crack propagation tests apparently obscure real differences in the toughness of the welded material as revealed by a Charpy V-Notch evaluation.[10]

TABLE III

THRESHOLD STRESS INTENSITY FACTORS*

MPa $\sqrt{m}$**

	K_Q		K_{Iscc}	K_{IHACZn}***		
	As-Rec'd	S.R. Furnace Cooled	As-Rec'd Material	As-Rec'd	S.R. Furnace Cooled	S.R. Air-Cooled
ESR						
Parent Metal	154-167	132-138	132	121	109	113-130
E12018 Stick Weld	121-124	120	94	50		
Simulated HAZ	121-125	143-151				
AMVD						
Parent Metal	132-136	126-132	121	97	95	98
E14018 Stick Weld	124	123		57	54	56
AX140 MIG Weld	132	99-122	99	55-61	62	55
Simulated HAZ	106	121-141		64		

* Threshold stress intensity factors greater than 50 MPa $\sqrt{m}$ not truly valid because specimen dimensions too small.

** Ksi $\sqrt{in}$ = 0.91 MPa $\sqrt{m}$

*** Specimen potential approx - 1.05v vs Ag/AgCℓ

ESR vs AMVD Metal

Table III shows that the crack propagation resistance under environmental conditions was significantly higher for the parent ESR than for the parent AMVD material. However, for a welded structure, it would normally be the lower properties of the welds which would control or limit a design so that the properties of the parent metal become less significant.

Effect of Corrosion

Unlike the 250 ksi maraging steel[1], free corrosion in sea water had only a moderate effect on reducing the resistance of HY130 to crack propagation. For the parent ESR and AMVD metals, the threshold stress intensity factors for free corrosion ($K_{I_{scc}}$) in sea water were only 10-15% lower than the measured dry fracture toughness indices (K_Q). The weld materials were affected more, but even here, the maximum reduction was 25%, and the $K_{I_{scc}}$ values of over 90 MPa $\sqrt{m}$ indicate very tough materials. By contrast, the $K_{I_{scc}}$ for the welded 250 ksi Maraging Steel was around 15 MPa $\sqrt{in}$, which represented about a 75% drop from its dry fracture toughness index.

Effect of Cathodic Protection

Cathodic protection at the potential of zinc (-1.05 volts vs Ag/AgCℓ) had considerably more effect than free corrosion on the resistance to crack propagation. For the parent metals, the threshold stress intensity index for crack propagation under cathodic protection was about 25% less than the measured dry fracture toughness index. For the weld materials, the drop was as much as 60%. Again however, it should be born in mind that the crack propagation threshold index $K_{I_{HAC}}$ of 50 MPa $\sqrt{m}$ for the poorest of the weld metals is still indicative of a tough material. By contrast the $K_{I_{HAC}}$ value for 250 ksi Maraging Steel was around 24 MPa $\sqrt{m}$.

Effect of Weld Material and Welding Procedure

From the limited data available from these investigations for the as-welded material, there does not seem to be much difference in the environmental cracking resistance of the three weldments; E12018 stock, E14018 stock and AX140 MIG.

The very limited data on simulated heat affected zone material indicates that this part of a welded HY130 structure is at least as resistant to environmental crack propagation as the welds themselves.

Effect of Stress-Relief Annealing

Neither of the two stress relief annealing treatments appeared to affect significantly the resistance of either the parent or welded HY130 alloys to crack propagation under cathodic protection of the potential of zinc (-1.05 volts vs Ag/AgCℓ).

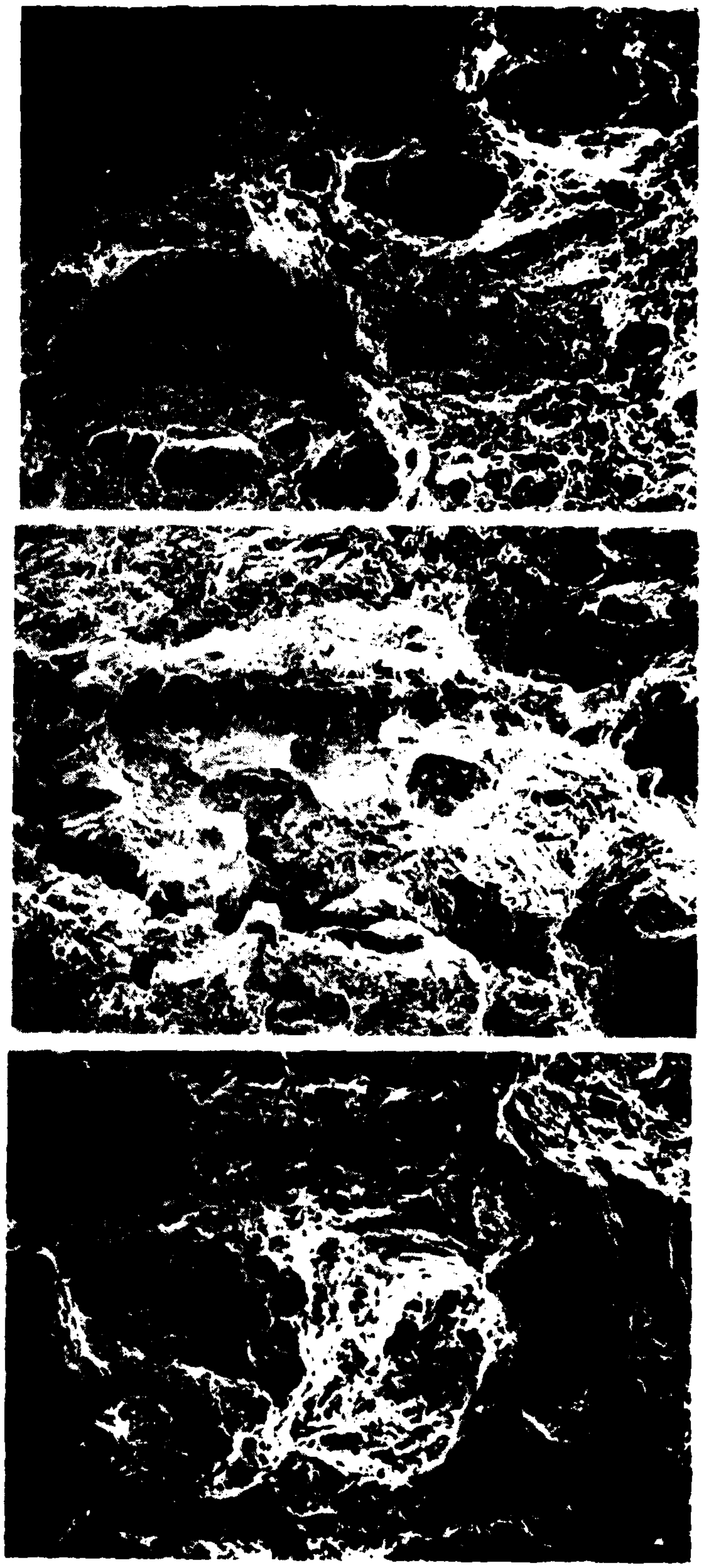
Fractography

Fracture of the HY130 specimens did not occur in a brittle manner. Shear lips extending up to 25% of the area of the fracture face (see Figure 5) indicated that the crack front in the 25 mm by 25 mm specimens was only partially under plane strain conditions.[6] The banded appearance of the welded material was due to the different weld passes. Stress corrosion and hydrogen cracking fracture surfaces showed no preferential or macroscopic branching crack paths.

Parent Welded

Figure 5. Typical parent and welded HY130 steel fracture faces. (Magnification 1.8x)

Figure 6. Fractographs of HY130 steel



a. dry fracture

b. SCC fracture

c. HAC Fracture magnification x260

Micrographs of the different fracture surfaces were obtained with the scanning electron microscope. Figure 6(a to c) shows the effect of SCC and HAC on the fracture surface. It can be seen that the fracture surface of the parent material exhibits the classic cup and cone features typical of ductile failure by microvoid coalescence. Stress relief heat treatment did not noticeably alter this feature. Comparison of the stress corrosion fracture surface and the hydrogen cracking fracture surface (Figures 6b and 6c) shows they are both predominantly transgranular cleavage with some micro branch cracking. The cleavage facets tend to be more distinct, however, for the hydrogen cracked surface, probably because corrosion of the fracture faces under SCC conditions would tend to obscure the facets. Also, the stress corrosion fracture appears to have some ductile tearing intermingled with the cleavage.

Fractographs of the welded specimens are harder to interpret because the surface topography will depend to a large extent on the microstructure where the cracking occurred. The microstructure can be markedly altered as a result of multiple pass welding. (See Figure 7).

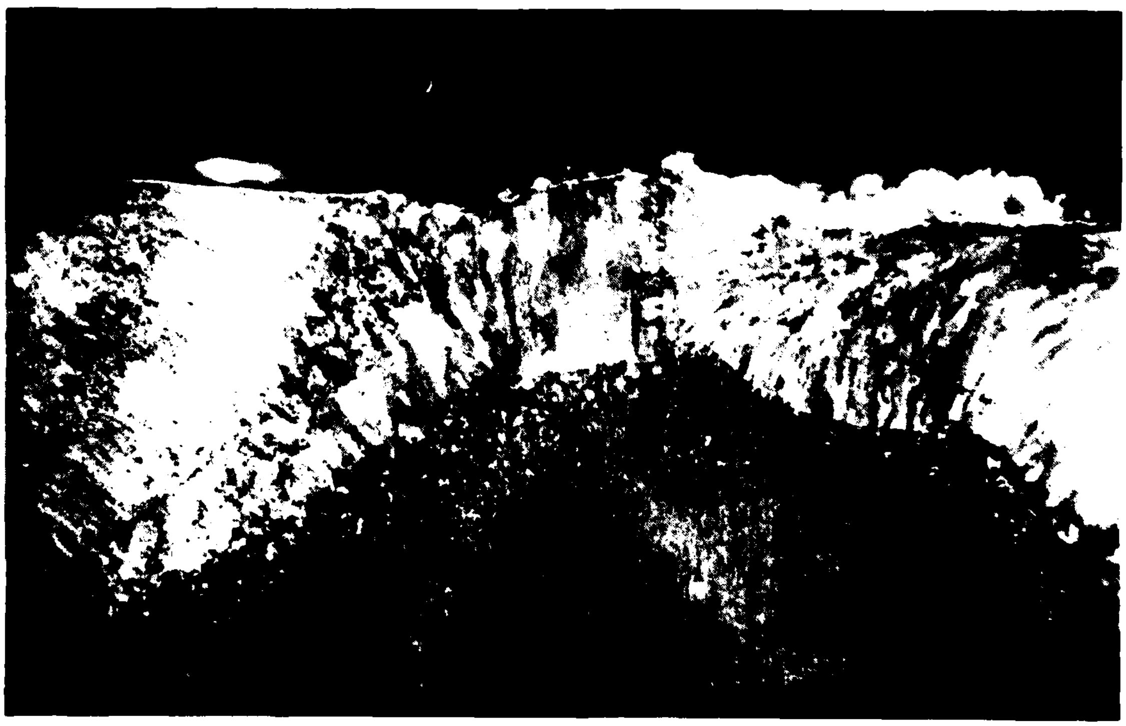


Figure 7. Micrograph of fractured weld specimen (Magnification 8x)

All weld fracture surfaces showed bands of intergranular and transgranular cleavage as well as large regions of dimple rupture. Figures 8 and 9 show fractographs taken from regions of dry fracture and HAC fractured specimens which had similar microstructures. Generally the MIG welded specimens started to crack in an intergranular manner (see Figures 8a and 8b), while cracking in the E14018 stick welded specimens tended to initiate in a transgranular manner (see Figures 9a and 9b).

It is significant that the fracture appearance of the weld specimens fractured under dry conditions and under cathodic protection conditions were similar. Although the dry fractured specimens did appear to have a slightly larger percentage of dimple rupture, the overall appearance was the same.

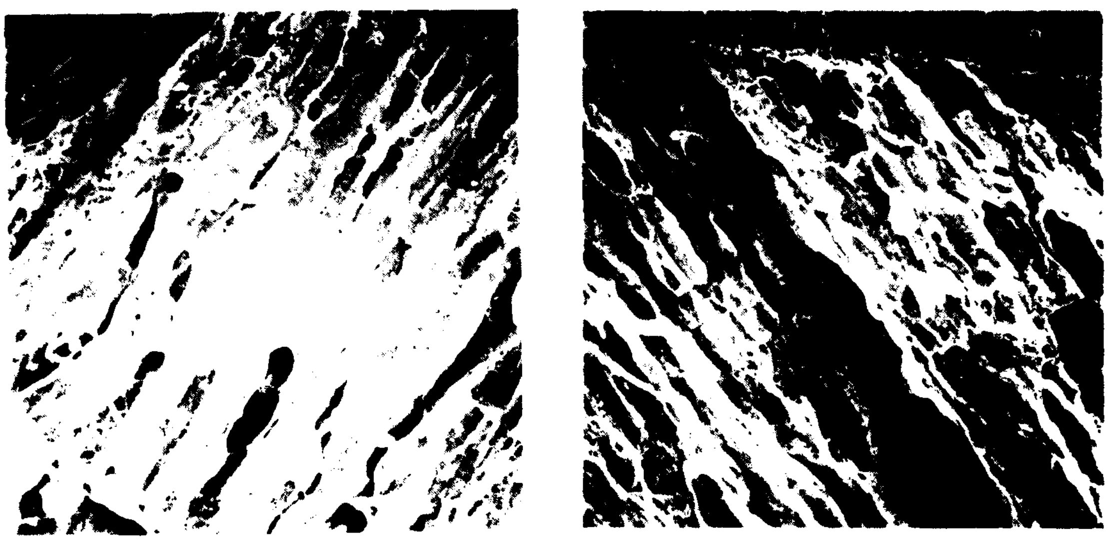


Figure 8.

a. Surface of AX140 MIG-weld fractured dry. (Magnification 180x)

b. Surface of AX140 MIG-weld fractured while under cathodic protection with zinc. (Magnification 150x)

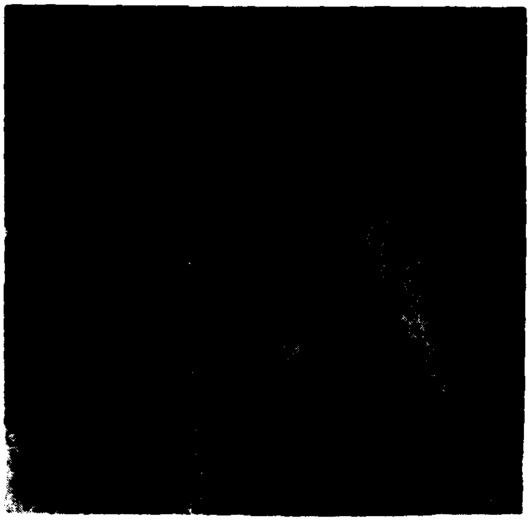


Figure 9

a. Surface of E14018 Stick-weld fractured dry. (Magnification 180x)

b. Surface of E14018 Stick-weld fractured while under cathodic protection with zinc. (Magnification 170x)

Mechanism of Cracking

The mechanism of environmental cracking is still controversial, but for high strength steels there appears to be some agreement with a hydrogen embrittlement mechanism. It is known that environmental cracking rates of various high strength steels increase with anodic polarization and can decrease or increase with cathodic polarization, depending on the level of polarization. (Reference 4, page 125). Initially it was thought this variation under cathodic protection indicated a dual mechanism of active path corrosion and hydrogen embrittlement. However, Smith et. al.[11] have shown that under anodic or cathodic polarization the solution chemistry at the crack tip is always favourable for the reduction of hydrogen. Hydrogen absorption by ASI 4340 steel has been observed under anodic polarization.[12]

The similarity between SCC fracture surfaces and hydrogen fracture surfaces of the parent HY130 steel would appear to support the above argument. The observation that the cleavage facets are more distinct on the hydrogen fractured surfaces is probably due to corrosion having occurred on the stress corrosion fracture faces during the test. The stress corrosion fracture

surfaces also appear to have some regions of ductile tearing (see Figure 6b). This variation could indicate that the corrosion and hydrogen reduction reactions are localized resulting in some areas being embrittled while others are not. The ductile tearing would not be expected to occur under hydrogen charging conditions because the flux of hydrogen atoms could be more uniform.

While there is a great difference between the dry fracture faces and the environmentally fractured surfaces of the parent HY130, the fracture faces of welded material are similar for both conditions. This similarity can be explained as follows. Petch[13] has proposed that hydrogen embrittlement occurs by hydrogen atoms diffusing through the lattice to adsorb on the surface of dislocation pile-ups, lowering the energy required to create a crack. Townsend[5] further expanded on this theory by proposing that the hydrogen atoms, in effect, lower the stress required to cause brittle cleavage. For a material such as HY130, which normally behaves in a ductile manner, the plastic flow stress is lower than the cleavage stress. However, upon introduction of hydrogen the stress required to initiate brittle cleavage will be lower than the plastic flow stress and a cleavage failure will result. If a material normally fails by cleavage (like sections of the weldments), the introduction of hydrogen, while not changing the fracture mechanism, lowers the stress required to cause cleavage failure. The hydrogen causes a reduction in the observed K_Q but the dry fracture face and the hydrogen fracture surface would be similar in appearance.

CONCLUSIONS

1. In seawater, under free corrosion or cathodically protected conditions, cracks will not initiate in either the ESR or AMVD forms of HY130, or their weldments or heat affected zones, at static stresses up to the yield.
2. For the HY130 alloys and weldments corroding freely in sea water, the lowest threshold stress intensity index K_{Iscc} for crack propagation was 94 MPa $\sqrt{m}$* for the E12018 weldment. This is a very high threshold for a high strength steel.
3. For the HY130 alloys and weldments under cathodic protection in sea water, the lowest threshold stress intensity index for crack propagation was 50 MPa $\sqrt{m}$ (also for the E12018 weldment). Again, this threshold is relatively high for a high strength steel.
4. Based on the limited data from these environmental cracking investigations, there is little difference between E12018 stock, E14018, or AX140 MIG welds.
5. On the basis of the evaluation carried out to-date, a stress-relief anneal of two hours at 620°C followed by furnace or air cooling does not markedly affect HY130's environmental cracking resistance under static loading.
6. Fractographic evidence supports a hydrogen induced cleavage mechanism for both stress corrosion cracking and cracking under cathodic protection, for the HY130 alloy and its weldments.

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*K_{Iscc} values greater than 50 MPa $\sqrt{m}$ not truly valid because specimen dimensions too small.

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13. ABSTRACT The Electroslag Refined (ESR) and the Air-Melt Vacuum Degassed (AMVD) forms of the HY130 low alloy steel, along with three weldments, AX140 MIG and E12018 and E14018 stick, have been evaluated for their resistance to environmental cracking under static loading in natural sea water.

It was found that under both free corrosion and under cathodically protected conditions, cracks will not initiate in either the ESR or AMVD alloys, their heat-affected zones, or the three weldments, at static stresses close to the yield.

For freely corroding HY130 alloys and weldments the lowest threshold stress intensity factor (K_{Iscc}) for crack propagation was 95 $MPa\sqrt{m}$ for the E12018 stick weldment. The lowest threshold (K_{IHAC}) for crack propagation under cathodic protection at zinc potential was $50a\sqrt{m}$ (also for the E12018 stick weldment). Both of these thresholds are relatively high for high strength steels.

The tests indicated that a stress relief anneal of two hours at 620°C, followed by either furnace or air cooling, does not markedly affect the environmental cracking resistance under static loading of the two types of HY130 parent material, or of the three weldments.

For the HY130 alloys and the three weldments studied, fractographic evidence supports a hydrogen-induced cleavage mechanism for both stress corrosion cracking and cracking under cathodic protection.

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KEY WORDS

CORROSION
HY130 STEEL
ENVIRONMENTAL CRACKING
FRACTURE TOUGHNESS
HY130 WELDMENTS
CRACK INITIATION

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